NRC Earth Science Decadal Study RFI Mission Concept

Climate Calibration Observatory
"NIST in Orbit"

Concept Team

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Climate Calibration Observatory

1.0 Summary and Mission Purpose

We have a major disconnect between high accuracy NASA research missions for short periods of time, and lower accuracy NOAA weather missions for long periods of time. Neither set of observations is designed to eliminate climate record gaps. Data continuity and stability over time is not likely to meet climate requirements (e.g. references (1) through (7)). High accuracy and stability climate calibration is expensive and is completed as the last steps before delivery of a space based instrument that is typically behind schedule and over budget (e.g. EOS, NPOESS….). Further, for NPOESS in particular, climate stability metrics are included in the requirements but are not "critical" requirements. This means that they can (and most likely will) be sacrificed to save budget and time. The NPOESS VIIRS imager instrument early in its design eliminated the ability to observe the moon for stability checks used routinely by SEAWIFS and MODIS. NPOESS has a primary weather mission that cannot be sacrificed to a climate mission. NASA on the other hand cannot maintain long records of research satellite data unless mandated by Congress (e.g. TOMS ozone). As a result there is no designed climate observing system, but rather one of fortune and misfortune.

The cost to implement climate quality calibration and stability (typically 0.1% level) is much more stringent and expensive than weather quality calibration. For example: weather forecast initialization receives no benefit from data that is stable at 0.01K, versus data that slowly drifts by 0.1K per decade. But the entire global climate surface temperature signal is order 0.1K per decade. Radiative forcing of climate is 0.6 W/m^{-2} per decade (IPCC, 2001, nominal scenario). As a result, a change in global net cloud radiative effects of 0.15 Wm^{-2} per decade is a cloud feedback of 25%: increasing or decreasing climate sensitivity. But mean radiative fluxes are 100 Wm^{-2} for solar reflected shortwave (SW) and 240 Wm^{-2} for thermal emitted longwave (LW) radiative flux at the top of the atmosphere. The corresponding radiative effect of clouds is 50 Wm^{-2} for SW and 30 Wm^{-2} for LW. So the simple global mean stability requirement is 0.15 out of 50 = 0.3% per decade for SW flux and 0.15 out of 30 = 0.5% per decade for LW flux. This requirement is just to hold uncertainty in global cloud feedback to +/- 25%. Understanding the source of this cloud feedback will require similar accuracies in cloud fraction, height, optical depth, etc. A summary of such stability requirements, each tied to key climate forcing, feedback, or response can be found in the multi-agency report on Satellite Instrument Calibration for Measuring Global Climate Change (6,8). The report summarizes both the physical variable accuracy and stability, as well as the related instrument measurement value. Requirements for stability per decade in deg K for thermal infrared measurements, in equivalent instrument gain for the other measurements. So for example, 1% stability for vegetation is an instrument gain stability of 1%, so that vegetation with a global average spectral albedo of 0.10 could have change detected over a decade if its albedo changed from 0.100 to 0.101.

Variable	**Stability/Decade (Instrument gain change in % or deg K)**
TOA SW and LW Fluxes	0.3 to 0.5%
Cloud Optical Thickness	1%
Cloud Temperature	0.2K
Surface albedo	1%
Ocean color	1%
Vegetation	1%
Water Vapor	0.03K
Tropospheric Temperature	0.04K

Space and time variability in temperature, humidity, clouds, and radiation put very stringent sampling requirements on contiguous global coverage, diurnal sampling, etc. The costs of marrying research quality with operational global sampling spiral out of control rapidly. We conclude that a new method is needed to achieve these types of calibration and stability for climate data records (CDRs) that are key to climate research.

We suggest an alternative solution called the **Climate Calibration Observatory**. The mission provides NIST-like transfer radiometer time series that underfly all orbiting weather and research satellites. The transfer radiometers cover the full solar and infrared spectrum to allow calibration of radiometers, spectrometers, and interferometers from 0.3 to 100 μm: the full earth spectrum that drives climate change from solar scattering/absorption through thermal emission/absorption. This observatory is designed not to sample the earth but to calibrate other radiometers in orbit. In this mode field of view size is large (higher signal to noise, smaller optics, less mass and power), accurate pointing control is needed but not full earth scanning (less mass and power), and a dedicated small spacecraft is used to allow full control of spacecraft pointing modes for regular lunar, solar, and instrument intercalibrations (unlike NPOESS or even the large EOS Terra and Aqua missions). As a result, the instruments can be small, light, and fit on a small mission. The mission is clearly research quality focused, but would provide great direct benefit to NPOESS, geostationary satellites, and international missions for climate applications. Large cost savings would be obtained when compared to each individual instrument being required to reach climate accuracy.

Why is this possible now? Recent developments and experience have advanced many of the required areas including:

a) Interferometers and blackbody calibration (e.g. Goody, Anderson, Smith, Mlynczak, Harries)
b) Long time series of earth viewing active cavities (ERBS, Wielicki) showing agreement with deep ocean heat storage of 0.1% interannual over a decade.
c) Long time series of overlapped solar irradiance (ERBS, SORCE, many others)
d) New solar spectral irradiance designs (SORCE TIM and SIM, Pilewskie and Harder)
e) Improved broadband thermistor bolometers (CERES, Priestley, Wielicki)
f) Problems with current imagers for ocean color and improvements using lunar stability with current imagers (MODIS, SEAWIFS, Siegel, McClain)

g) Experience with multiple satellite platform intercalibration using pointable and programmable CERES instruments to align with other leo and geo instruments (Priestley, Harries)

We conclude that the "missing dimension" in climate research is to drive the accuracy of calibration and stability of the radiometers used for global climate observations. For climate, the "calibration" dimension is more important than achieving higher spatial resolution, angular resolution, or time resolution. The Climate Calibration Observatory is designed to attack this missing link in climate data records.

2.0 Climate Calibration Observatory Mission Characteristics

2.1 Size Mission

a) Small (< $200M) to Medium ($200M to $500M) depending on the length of time the missions shall continuously provide the climate calibration record.

2.2 Orbit:

a) 750 km altitude, precessing, 64.02 degree inclination, exactly four full 24-hour precession cycles/yr,
b) allows calibration of all orbiting platforms: sunsynch, geo, other precessing, etc

2.3 Continuity and Overlapping Observations

a) Two observatories at any one time to assure overlap. 6 hour orbit separation in local time (same precessing orbits and inclination).
b) Launch on failure of one of the key instruments or spacecraft
c) Design life of 6 years for instruments and spacecraft
d) Small Pegasus launch missions to allow launch on demand within 3 months of failure. Optional: in orbit spare. Decide based on cost effectiveness. Gap risk estimated as 1% over 45 years.

2.4 Reference Calibration Instruments:

a) Solar reflected spectrum (0.4 to 3 μm). Linear detectors to 0.1%
(e.g. SORCE SIM spectral measurement modified to earth viewing design)
b) Infrared emitted spectrum (3 to 100 μm). Linear detectors to 0.1%
(e.g Anderson INTESA, Mlynczak FIRST interferometers).
c) Active Cavity total channel (0.3 to 100 μm). Linear detectors to 0.1%
(e.g. ERBS MFOV: 500km fov in earth view, SORCE solar irradiance)
d) Active Cavity shortwave channel (0.3 to 3.5 μm). Linear detectors to 0.1%
(e.g ERBS MFOV: 500km fov in earth view)

2.5 Field of View, Pointing, and Matching Fields of View in Angle/Time/Space

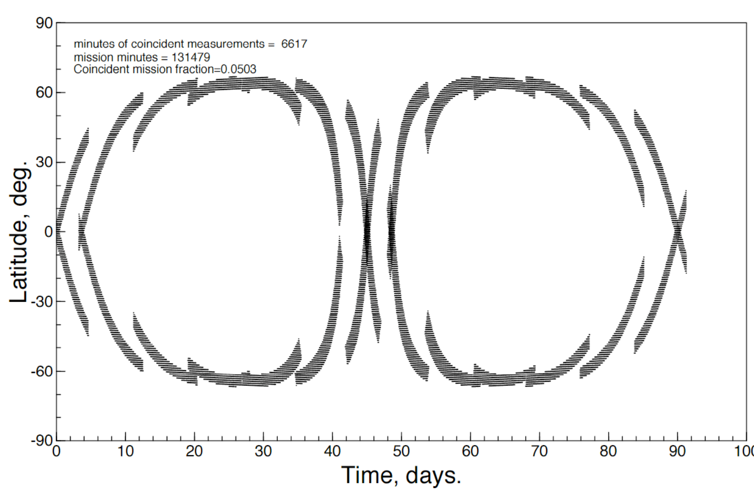
a) 100km diameter at nadir for the most accurate spectrometers. Accurately measure point spread function (spatial/angular response function for matching to other instruments). 100km fov assures viewing angle variations to within +/- 3 degrees from 750km orbit.
b) 500km at nadir for the active cavities. Similar to ERBS medium fov cavity.

c) Large fov allows accurate integration of smaller fovs (1 imagers to 20km sounders) into the reference instrument fov with very high spatial matching. CERES has demonstrated this with MODIS (1km) => CERES (20km), and with CERES (10 and 20km) => 100km grid. Spatial sampling studies using CERES 20km fov in a 100km region show that spatial sampling noise in earth viewing matches of two radiometers can be reduced to 0.5% for thermal infrared and 1.5% for solar reflected radiance (1 sigma, single 100km sample matches). Between 10 and 100 samples are sufficient to reach climate accuracy for stability intercalibration for global mean values.

d) 1 km for lunar viewing solar spectra, with 100km coverage (allows matching to the larger fov in item a)). This is used to bootstrap the spectral lunar stability check (moon has 6km equivalent diameter for a leo earth viewing instrument) to the larger fov standard spectrometer. Uses long dwell time in lunar views to keep signal to noise large and eliminate large optics. Also only need to cover 100km domain, so 256 linear detector array is sufficient to scan the moon and 100km spectrometer fov (including the full point-spread function)

e) Pointing control to 500m equivalent distance on the earth surface when viewed from orbit, and 100m pointing knowledge.

f) Allow pointing of the nominal "nadir" fields of view to a range of viewing zenith angles and azimuths: similar to the CERES instruments. CERES has demonstrated that this allows angle/time/space matched data from instruments in leo to geo, and from one leo to another leo, even when the orbit tracks seldom match in time/space at nadir view. This capability also allows calibration checks across the full swath of a multi-detector instrument, not just for a "nadir" detector. Orbits can be predicted ahead of time to plan such intercalibrations for each day and each coordinating spacecraft. CERES has demonstrated this capability by intercalibration with all 250 detectors on the Geostationary Earth Radiation Budget (GERB) instrument on Meteosat Second Generation (MSG), as well as for ScaRaB in low earth orbit (9), and for intercalibration of CERES on TRMM precessing and Terra sunsynchronous satellites in low earth orbit. Figure 1 below shows a sample of orbit crossing matches between the proposed Climate Calibration Observatory orbit and the EOS Aqua orbit, with matches within 5 minutes in time, and spatial matches within +/- 500km of the Aqua orbit track (i.e. within 35 degree viewing zenith angle of nadir). During a single precession cycle of 91.3 days, 5% of the orbit time is matched in viewing angle/time/space, for 6617 minutes of matched data that is distributed uniformly in local solar time and longitude, and covers all latitudes from 65S to 65N. The match latitudes and times are shown in Figure 1.



2.6 Radiometric Stability References

a) Lunar stability metric at constant phase angle, (e.g. SEAWIFS)
b) Solar stability metric (cavity direct view, solar spectrometer direct and diffuser) (e.g. ERBS, SORCE, MODIS)
c) On board lamps with multiple levels and trap detector monitors for stability.
d) Independent on board deep well blackbodies (not the simple concentric rings normally used) with multiple temperature levels (e.g. CERES, INTESA)
e) All calibrations performed through full optics/detector system (e.g. SORCE, ERBS, CERES)

3.0 Climate Calibration Observatory and the NRC Decadal Study Prioritization Criteria

3.1 Priority in Previous Studies

Climate record stability, absolute calibration, and the elimination of climate record gaps have been recognized as critical issues for the evolving climate observing system by many NRC reports (e.g. 1,2) the WMO Global Climate Observing System (3), the U.S. Climate Change Science Program (4) as well as the more recent IWGEO (5) and a recent multi-agency workshop on satellite calibration requirements for climate observations from space (6). The proposed mission would address these issues for most of the critical climate observations: those provided by spectral and broadband reflected solar and thermal infrared emission observations from space.

3.2 Contribution to Multiple Panel Themes

The ability to provide climate calibration and stability for many different research and operational weather instruments (e.g. NPOESS) would benefit a wide range of critical climate data: SST, ocean color, cloud properties, aerosols, temperature and water vapor profiles, surface vegetation, radiative fluxes. These improvements would impact the first 5 themes of the Decadal Study, and would be most critical to accomplish the objectives for the following three themes:

- Climate Variability and Change
- Earth Science Applications and Societal Needs
- Land-use Change, Ecosystem Dynamics, and Biodiversity

3.3 Contribution to Key Earth Science Questions

Highly stable and accurate climate data is relevant to ALL climate science questions. Improvements in calibration and stability will allow determination of key decadal changes such as:

- cloud feedback (decadal changes in cloud properties and cloud radiative forcing)
- changes in anthropogenic radiative forcing due to land use and aerosols
- snow and ice feedback (spectral and broadband albedo changes)
- water vapor feedback: including far-infrared spectrum dominated by water vapor emission from 20 micron to 100 micron wavelength.
- surface temperature and temperature profile climate response
- ocean biosphere response (ocean color)
- vegetation response changes

3.4 Contributions to Policy Making and Applications

Highly stable and accurate climate data is relevant to many climate policy issues. Ultimately, policymakers will respond more effectively when climate predictions are shown to more accurately predict highly rigorous and independently confirmed decadal changes in all key climate variables involved in climate forcing, feedback, and response. The examples in 3.3 include many of these key climate variables.

3.5 Contribution to Long-Term Monitoring of the Earth

This is the primary purpose of this mission. It takes advantage of recent advances in highly calibrated instrument design, spacecraft navigation, and intercalibration techniques to focus on instrument calibration as its own independent mission optimized to achieve climate required accuracy in radiometric stability and calibration for decadal change observations from a range of satellite systems, instruments, and satellite orbits. Relevant instruments include any that observe in the solar and thermal infrared spectral regions, from about 0.3 to 100 micron wavelengths.

3.6 Complements other Observational Systems

This mission concept represents a fundamentally new way to provide climate quality calibration and stability to meteorological satellites like NPOESS that provide data highly relevant to the climate system, but which do not have any critical requirement to maintain overlapping records or climate quality stability. The critical requirements for NPOESS are the weather observing requirements, and they take precedence over climate requirements. Given the fact that instrument calibration and characterization are some of the last tasks, budget and schedule risks will favor meteorological requirements and not climate. Accuracy requirements for weather observations are roughly a factor of 10 less stringent than for climate stability used in determining decadal time scale changes in the climate system. For example, decadal change in temperature is 0.1K, while 1K is sufficient for weather requirements at short time/space scales. In addition, a separate Climate Calibration Observatory allows reduced risks for other space missions. For example, climate quality missions typically find it very useful to perform special satellite operations such as pitch over maneuvers for verifying instrument zero levels against deep space (TRMM, Terra), or for stability checks using lunar or solar observations (SEAWIFS, Terra, ERBS). These operations are not allowed on the operational NPOESS weather systems. Even the EOS Aqua mission has not been able to perform such a maneuver because of concerns over changes in the performance of the AIRS instrument after changing the environment of its thermal cooling systems. Both NPOESS and AIRS refusal to consider deep space or lunar views for calibration are a result of the very different objectives and requirements of weather versus climate. Finally, there is no requirement on NPOESS to have overlapping observations. Launch is after failure of a key weather instrument. Since absolute accuracy of these instruments does not come close to decadal changes, overlap is critical and is one of the 10 satellite climate observing principles (e.g. NRC, GCOS, CCSP, IWGEO). Achieving overlap in orbit is very expensive and requires spare satellites in orbit that are regularly intercalibrated with current operational satellites. NPOESS cannot afford this approach and does not require it for weather observations. The Climate Calibration Observatory concept can bridge such gaps and tie the calibration of different instruments on successive spacecraft at decadal climate accuracy.

3.7 Cost/Benefit

This mission has the potential to save substantial costs in the global climate observing system. Reaching climate calibration for every satellite instrument is prohibitively expensive. Additional mass and power is needed for high accuracy independent calibration sources and targets. Additional costs to keep hot spares in orbit can be avoided by using the Climate Calibration Observatory to be the calibration bridge between successive missions by weather satellite systems such as NPOESS. Risk to large weather satellites is also reduced by allowing them to avoid special calibration spacecraft maneuvers (deep space scans, lunar and solar viewing pitch over maneuvers).

3.8 Degree of Readiness

While the major elements of the concept have been flown in space before, they have not all been used in a way that is optimal to a Climate Calibration Observatory. We are not aware of any technology development required, but Phase A studies would be needed to examine:

- Optics and design changes to TIM/SIM solar spectral irradiance observations to optimize for an Earth viewing mode with large field of view (100km fov is ~ 10 degrees, versus solar viewing with narrow field of view of ~ 1 degree.
- Compare ERBS medium field of view active cavity designed for viewing the earth and the sun, with the more recent TIM cavity design. A blend of the best aspects of both may be needed.
- Compare interferometer designs to optimize for calibration application: large fov to simplify signal to noise requirements and allow use of highly linear detectors (e.g. INTESA), far infrared capability (FIRST balloon flight results).
- Use the results of the Leonardo spectrometer design studies to examine optimization for a high spatial resolution solar spectrometer capable of using the moon as a stability target. For a spectrometer in low earth orbit (e.g. 700km), the angular diameter of the moon is equivalent to about a 6km nadir field of view. This is much smaller than the 100km used for the most accurate, stable, and linear transfer radiometer. But a small spectrometer could be built to transfer from the spatial scale of the moon at 6km to the 100km larger calibrator. The advantage of a mission like the Climate Calibration Observatory is that it could design a spectrometer with long lunar observation times each lunar month (same lunar phase) and therefore much simpler optics and signal to noise issues than for a spectrometer required to cover the entire earth. Again, the very different design paradigm of this mission allows new ways to look at previous instrument designs to make them dramatically smaller and more stable.
- Examine optimum orbits for intercalibration opportunities vs latitude, time of year, and a range of satellites including geostationary and low earth orbit.
- Examine instrument mass and power requirements when used for the climate calibration application.
- Examine the tradeoffs of using spacecraft reaction wheel roll/pitch/slew versus individual instrument pointing to match the viewing angle and location of other instruments when the spacecraft orbits overlap.

Spacecraft pointing control now routinely reaches 1km on the ground, with pointing knowledge ~ 100m. This is well within the requirement for matching the Climate Calibration Observatory radiometers to other missions.

3.9 Risk Mitigation and Strategic Redundancy

Risk reduction would be to reduce the IR spectrometer wavelength range if the far-infrared test of FIRST is not successful. If successful, the FIRST design will have reached TRL-6. The other risk reduction is the Leonardo based spectrometer for lunar viewing. For climate calibration, linearity is a critical requirement. This 0.1% or better linearity will be achieved in the large field of view cavities and spectrometer/interferometers by the nature of their detector types. The original Leonardo design detectors are of more traditional types and linearity is not currently known and may only reach a few percent instead of the desired 0.1%. In this case, the high spatial resolution lunar stability would be sufficient to transfer calibration to low reflectance applications like ocean color and some vegetation mapping, but not to the full dynamic range of clouds and snow/ice targets. In this case, the lunar stability check would only be relevant at climate accuracy for ocean color and vegetation applications.

Since the objective of this mission is decadal climate record calibration, the mission design is for 2 observatories to be in orbit at any one time. If one of the missions fails, a replacement is designed to be ready to launch within a few months on a small launch vehicle like a Pegasus. Nominal design life for instruments and spacecraft would be 6 years with 85% success likelihood. This means that the chance of both in-orbit missions failing within a single 3-month vulnerability window is very small: much less than 1%. For typical engineering risk analysis: an instrument design for 85% success over 6-years will have a success rate of 0.993 for a single 3 month period: i.e. $(0.993)^{(72/3)} = 0.85$. Any given 3 month period in the 72-month design life of an instrument then has an 0.7% chance of failure. Chance of the same instrument failing on two different spacecraft during the same 3-month period (which would cause a calibration record gap) is then $(0.007)^2$ or well less than 0.1%. A larger risk would be the ~ 3% launch failure risk for the replacement mission. Scenarios of this type should be studied to design a system with total risk of a gap of less than 1% over 20 years. This is likely to be achieved with 2 missions on orbit, and the capability to launch hot spares when an instrument fails. The analysis will have to consider all possibilities of instrument loss, spacecraft loss, and launch failure.

3.10 Contribution to other National and International Activities

Since this mission will not "map" the Earth in the manner of most space missions, it will not be a replacement for other weather or climate observing missions. It will, however, add value to many space-based missions in applying their global sampling to a wide range of climate research and applications.

4.0 Concept Team Roles and Expertise

Member	Role	Expertise
Bruce Wielicki	Concept Lead	CERES P.I., CALIPSO, Cloudsat Co-I.
Kory Priestley	Broadband Calibration	ERBS Cavities, CERES calibration
Peter Pilewskie	Solar Spectral Measurement	SORCE SIM/TIM, Aircraft spectrometers
Jerry Harder	Solar Spectral Measurement	SORCE SIM/TIM instrument
Francesco Valero	Solar Calibration	DISCOVR SW Cavity
Joe Rice	Solar Calibration	NIST radiometric standards
Jim Anderson	Infrared Interferometry	INTESA aircraft interferometer
Martin Mlynczak	Far-Infrared Interferometry	FIRST balloon interferometer
John Harries	Broadband, Far-IR	GERB, Far-IR aircraft interferometer
Warren Wiscombe	Solar Spectrometer/Imager	Leonardo high resolution spectrometer lead
Dave Siegel	Solar spectral calibration	SEAWIFS ocean color
Charles McClain	Solar spectral calibration	SEAWIFS, MODIS, VIIRS ocean color
Thomas Stone	ROLO Lunar Spectral Model	SEAWIFS, MODIS stability vs moon
Thomas Karl	Climate Observing Principles	General climate requirements
John Bates	Satellite climate trends	IR spectra for water vapor and temperature
Kevin Trenberth	Climate Observing Principles	General climate requirements
Bruce Barkstrom	Broadband Calibration	ERBE P.I., previous CERES P.I.

5.0 References

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